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Farmers' precision pesticide technology adoption and its influencing factors: Evidence from apple production areas in China

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Abstract

The research aimed to understand farmers' willingness to adopt (WTA) and willingness to pay (WTP) for precision pesticide technologies and analyzed the determinants of farmers' decision-making. We used a two-stage approach to consider farmers' WTA and WTP for precision pesticide technologies. A survey of 545 apple farmers was administered in Bohai Bay and the Loess Plateau in China. The data were analyzed using the double-hurdle model. The results indicated that 78.72% of respondents were willing to apply precision pesticide technologies provided by service organizations such as cooperatives and dedicated enterprises, and 69.72% were willing to buy the equipment for using precision pesticide technologies. The results of the determinant analysis indicated that farmers' perceived perceptions, farm scale, cooperative membership, access to digital information, and availability of financial services had significant and positive impacts on farmers' WTA precision pesticide technologies. Cooperative membership, technical training, and adherence to environmental regulations increased farmers' WTP for precision pesticide technologies. Moreover, nonlinear relationships between age, agricultural experience, and farmers' WTA and WTP for precision pesticide technology services were found.

Keywords: precision technologies, apple production, precision pesticides, willingness to adopt, willingness to pay

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1. Introduction

Apple is the fourth most economically important fruit in the world (Forge *et al.* 2016; Teixeira *et al.* 2020). However, pesticide residues in apples have raised human health and food safety concerns (Drogué and DeMaria 2012; Fan *et al.*

2014, 2015). For example, 16.4% of Polish apple samples were reported to contain multiple pesticide residues, which increased the potential negative impacts on human health associated with unpredictable toxicities of chemical mixtures (Lozowicka 2015). According to the data in National Bureau of Statistics of China (NBSC 2021), China is the world's largest apple production and consumption country, with a yield of 45.97 million tons in 2021. At the same time, intensive pesticide use has been reported in the fruit sector (Foong *et al.* 2020). Research has been focusing on developing agricultural practices to achieve sustainable production in China's agricultural sector, which enables pesticide use reduction in line with China's sustainability targets. One area of research has been the development of precision pesticide technologies, using advanced technologies, such as variable-rate spraying control systems and target spraying technologies, to observe, analyze, and react to intra-field variability in agricultural production (Li Z *et al.* 2018). Precision pesticide technologies can improve agricultural performance, including the reduced use of chemical pesticides and other agricultural inputs, which may be associated with potential economic and environmental benefits contributing to the sustainable development of agriculture (Li C *et al.* 2018).

While precision technologies are available to reduce pesticide use in apple production (Cisternas *et al.* 2020), potential barriers to technology adoption may result in these benefits not being realized. For example, high costs of adoption and implementation may cause low adoption rates (Barnes *et al.* 2019). A series of factors that could affect end-users' adoption willingness of precision agricultural technologies have been identified. They can be classified into three categories: farmer characteristics (Mondal and Basu 2009; Paudel *et al.* 2020), farm management practice characteristics (Barnes *et al.* 2019), and external characteristics. In addition, researchers have also explored producers' and farmers' willingness to pay (WTP) for precision agricultural technologies. For example, Hudson and Hite (2003) used a contingent valuation survey to elicit WTP for a package of precision technologies and found that producers' WTP was significantly lower than current technology prices.

To date, limited research has accessed both farmers' willingness to adopt (WTA) and WTP for precision technologies within an integrative framework. Farmers' WTA and WTP regarding the technology adoption may be viewed as two independent decisions, where influencing factors may vary. There is evidence that farmers may use agricultural technologies through either purchasing the equipment to implement the technologies themselves or paying for the services provided by the relevant organizations (Yitayew *et al.* 2021). For example, adopting precision pesticide technologies *via* a service provider may be perceived as easier and more convenient by farmers, incurring less financial investment than purchasing the equipment and investing in training on how to use it (Cisternas *et al.* 2020). Against this, longer-term investment in "on farm" skills may be perceived by farmers to increase long-term profitability and economic returns. Information about farmers' preferences regarding precision pesticide technology adoption is needed to design effective strategies, to improve the adoption rate of precision technologies and deliver positive safety and environmental benefits.

The research aimed to explore farmers' WTA and WTP for precision pesticide technologies and understand the determinants of farmers' decision-making. First, the research aimed at assessing farmers' WTA and WTP for precision pesticide technologies either as a service provided by others or a direct-use method by the farmers themselves. Second, the research sought to identify the factors which influenced farmers' WTA and WTP for the technologies. A double hurdle model was adopted (Teklewold *et al.* 2006; Wang *et al.* 2020), which can be applied to analyze independent decision-making stages.

2. Data and methods

2.1. Theoretical framework

Tey and Brindal (2012) applied systematic review methodology to categorize the determinants of precision technology adoption into four groups, including socio-demographic factors, subjective perceptions, technological features, and institutional characteristics. Pathak *et al.* (2019) presented a classification containing several adoption determinants, including communication and influence, outer context, adopter characteristics, linkage and more. Even though the two classifications are not identical, they both focus on the prevalence of three factors: farmer characteristics, farm management practice characteristics, and external factors.

Farmer characteristics (e.g., gender, age, education level, farming experience, and farmers' perceptions of the risks associated with pests and diseases), can potentially influence their adoption of farming technologies (Feder and Umali 1993; Suvedi *et al.* 2017; Chen *et al.* 2018; Li *et al.* 2020). In addition, farm management practice characteristics, such as the farming scale, size of land plots, and available labor force, may influence decisions associated with innovative technology adoption (Khanna and Kaur 2019). External factors linked to environmental policies, financial support for technology adoption, and technical training, have been found as significant predictors of providing a favorable external environment to encourage farmers to adopt advanced technologies (Foster and Rosenzweig 2010; Orea *et al.* 2015). A theoretical framework was developed to assess the impact of intrinsic and external factors on farmers' WTA and WTP for precision pesticide technologies (Fig. 1).

2.2. Model selection

Farmers' decisions regarding precision technology adoption were assumed to occur in sequential stages. The first stage assessed "whether they would like to adopt precision pesticide technologies" (WTA). If the decision was positive, the second stage assessed "how much they were willing to pay for precision pesticide technologies?" (WTP). Dichotomous choice models such as the Probit Model have been widely used to estimate the probability of adoption and its determinants; the Poisson Count Regression Model (PCRM) and Ordinary Least Squares estimation (OLS) have been used to analyze the factors affecting individuals' WTP (Ali and Ali 2020; Pleeging *et al.* 2020). Methods such as the Heckman Model can achieve a two-stage estimation regarding the decision-making of technology adoption; thus, the two processes are not independent of each other, and the error in the first stage "WTA" will transfer to the second stage "WTP". The basic hypothesis about the decisions of WTA and WTP for the technologies are two independent decisions. Cragg (1971) proposed the double-hurdle model based on the assumption that individuals' WTA and WTP were independent decision procedures. The double-hurdle model was applied to analyze the factors influencing farmers' WTA and WTP for technology adoption (Burton *et al.* 1994; Teklewold *et al.* 2006; Ghimire and Huang 2015).

Farmers' WTA precision pesticide technologies were initially investigated as a dichotomous choice. Subsequently, their WTP was assessed if WTA was positive. A Probit model was employed in the first stage, followed by a truncated regression model in the second stage. In decision-making involving two stages, a complete decision to adopt technology can be made based on the decisions made at both stages. The equation of "WTA" and "WTP" are two independent equations, avoiding endogeneity between these equations. The equations are defined as follows:

First, the equation of "WTA" can be expressed as:

$$prob\{y_i=0|x_{1i}\}=1-Ø(x_{1i}\alpha) \quad (1)$$

$$prob\{y_i>0|x_{1i}\}=Ø(x_{1i}\alpha) \quad (2)$$

Eq. (1) means that farmers are not willing to adopt precision pesticide technologies, whose answer to "WTA" is zero; eq. (2) indicates that farmers are inclined to adopt precision pesticide technologies, where "WTA" is greater than zero; $Ø(\cdot)$ is the cumulative function of the standard normal distribution; y_i is the dependent variable, "whether to adopt"; x_{1i} is independent variables; α indicates the corresponding coefficient to be estimated; *i* means the *i*th sample.

Second, "farmers' WTP for precision pesticide

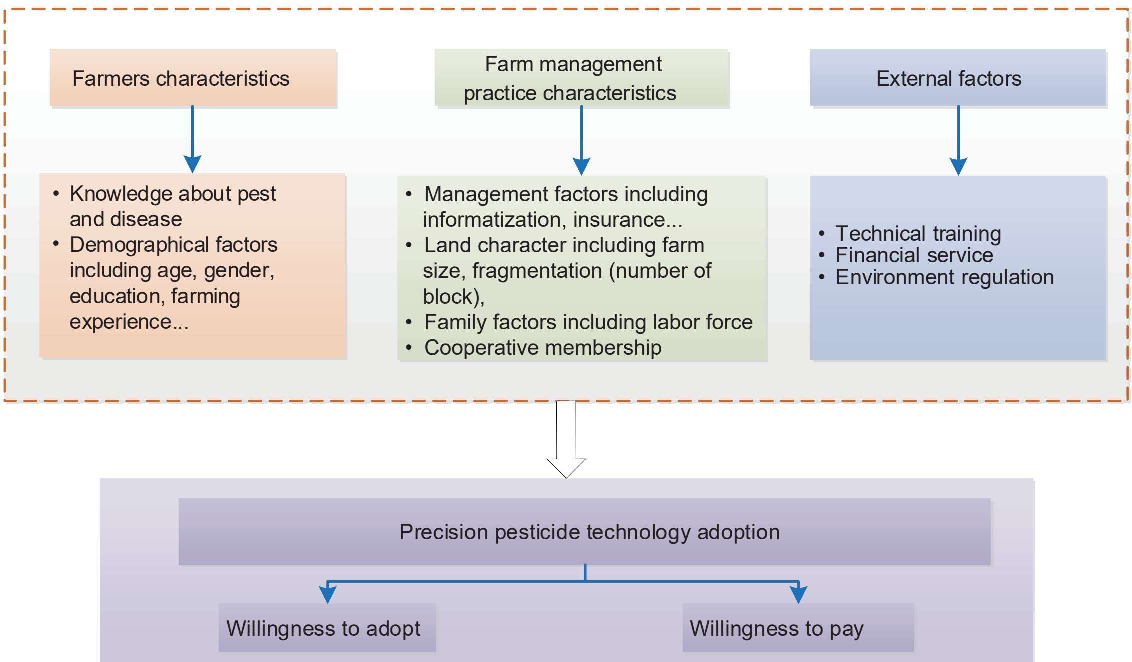

Fig. 1 Conceptual model for farmers' precision pesticide technology adoption.

technologies" is calculated as follows:

$$E\{y_i|y_i>0,\ x_{2i}\}=\beta x_{2i}+\delta\lambda(\beta x_{2i}/\delta) \quad (3)$$

Eq. (3) indicates the conditional expectation and "farmers' WTP for precision pesticide technologies", where $\lambda(\cdot)$ is the inverse Mills ratio; x_{2i} represents independent variables; β represents the corresponding coefficient to be estimated; δ represents the standard deviation of the truncated normal distribution.

Based on eq. (1) to eq. (3), the log-likelihood function can be established as follows:

$$\ln L=\sum_{y_i=0}\{\ln[1-\phi(\alpha x_{1i})]\}+\sum_{y_i>0}\{\ln\phi(\alpha x_{1i})-\ln\phi(\beta x_{2i}/\delta)-\ln(\delta)+\ln\{\phi[y_i-\beta x_{2i}/\delta]\}\} \quad (4)$$

In eq. (4), $\ln L$ represents the log-likelihood function value. According to eq. (4), the relevant parameters are calculated through maximum likelihood estimation.

2.3. Measurement variables

Dependent variables Purchasing technological equipment and associated materials is a direct way for farmers to adopt new agricultural technologies (Bukchin and Kerret 2020). In China, rural–urban drift, particularly among younger people, has resulted in an aging farming community and "succession" issues in farming. Older farmers may be less willing to invest in new agricultural technologies and skills. Therefore, purchasing services from professional agricultural enterprises or cooperatives may be an effective way for older farmers to adopt and implement new technology, reducing investment risks and saving farming costs (Ma *et al.* 2018). Farmers' adoption decisions associated with precision pesticide technologies were assessed in two ways: analyzing farmers' WTA and WTP for the equipment and evaluating the services provided by professional agricultural enterprises or cooperatives. Given the heterogeneity of these two potential determinants of decision-making, estimations for technical equipment and service provision were conducted separately[1].

First, farmers' WTA precision pesticide technologies was investigated by asking, "In the next five years, are you willing to adopt the services of precision pesticide technologies provided by service organizations, such as cooperatives or enterprises?" Participants answered on five-point Likert scales anchored by one to five (strongly unwilling to adopt to strongly willing to adopt). Whether to adopt precision pesticide technologies was categorized into binary variables: farmers who were willing or strongly willing to adopt precision technologies were classified as technology adopters, otherwise, they were clarified as non-adopters.

Second, if farmers' answer in the first decision-making stage was "willing or strongly willing to adopt," then the second decision-making stage, "WTP for the technologies" would be investigated. The question was, "If you are willing to adopt precision pesticide technologies through buying services, how much would you be willing to pay for this kind of services every year (CNY mu^{-1})[2]?". WTP (CNY mu^{-1}) was divided into the following intervals: 25 CNY mu^{-1} below, 25 to 50 CNY mu^{-1}, 50 to 70 CNY mu^{-1}, 75 to 100 CNY mu^{-1}, 100 to 150 CNY mu^{-1}, 150 to 200 CNY mu^{-1}, 200 to 250 CNY mu^{-1}, 250 to 300 CNY mu^{-1}, 300 to 350 CNY mu^{-1}, 350 to 400 CNY mu^{-1}, 400 to 450 CNY mu^{-1}, 450 to 500 CNY mu^{-1}, and 500 CNY mu^{-1} and above, based on a preliminary investigation using assessments of cost provided by experts and agricultural service providers. In the second stage, double-bounded dichotomous choice valuation was employed to investigate farmers' WTP (Aikoh *et al.* 2020). Farmers were asked if their WTP was above an initial bid value. If their answer was "yes," a follow-up question was asked to assess if their WTP was above a second and higher bid value until they said "no;" if farmers' response to the initial value was "no," a follow-up question asked if their WTP was above a lower bid value until a "yes" answer reached (Herriges and Shogren 1996). The mean value of each price interval was used to calculate farmers' WTP for precision agricultural technologies.

Independent variables The independent variables included in the double-hurdle model were selected based on the literature on precision pesticide technologies and farmers' adoption practices. They were divided into four categories: personal characteristics, perceived perceptions, farm management practices, and external characteristics. The definition of variables and descriptive statistics are presented in Table 1, and the impacting pathway of variables is shown in Appendix A.

[1] The question format for purchasing precision pesticide technologies was similar to that of services. For WTA, respondents were asked, "In the next five years, are you willing to apply precision pesticide technologies through buying the corresponding equipment?" For WTP, farmers were asked, "If you are willing to adopt precision pesticide technologies through buying the equipment to be used for five years, how much would you be willing to pay for buying this equipment every year? The money can be used for the cost of depreciation and maintenance, CNY yr^{-1}." The WTP was divided into the following price intervals: 1 000 CNY yr^{-1} below, 1 000 to 2 000 CNY yr^{-1}, 2 000 to 3 000 CNY yr^{-1}, 3 000 to 4 000 CNY yr^{-1}, 4 000 to 5 000 CNY yr^{-1}, 5 000 to 10 000 CNY yr^{-1}, 10 000 to 15 000 CNY yr^{-1}, 15 000 to 20 000 CNY yr^{-1}, 20 000 to 25 000 CNY yr^{-1}, 25 000 to 30 000 CNY yr^{-1}, and 30 000 CNY yr^{-1} and above.

[2] 1 mu=0.0667 ha.

Table 1 Definition of variables and descriptive statistics

Variable	Description	Mean	Std. dev.
Dependent variables			
Whether to adopt the services	In the next five years, are you willing to adopt the services of precision pesticide technologies provided by service organizations such as cooperatives and enterprises? (1=willing to adopt, 0=not willing to adopt)	0.787	0.410
Whether to adopt the equipment	In the next five years, are you willing to buy the equipment of precision pesticide technologies? (1=willing to adopt, 0=not willing to adopt)	0.697	0.460
WTP for purchasing service	If you are willing to adopt precision pesticide technologies through buying services, how much would you be willing to pay for buying this kind of service every year? (CNY mu^{-1})	114.656	122.528
WTP for purchasing equipment	If you are willing to adopt precision pesticide technologies through buying the equipment, how much would you be willing to pay for buying this kind of equipment every year? (CNY yr^{-1})	2 670.642	4 827.946
Personal characteristics			
Gender	Gender of the respondents (1=male, 0=female)	0.873	0.333
Age	Age of the respondents in years (continuous)	52.299	9.454
Education	Years of formal schooling (continuous)	8.164	3.381
Farming experience	Years of the respondents engaged in planting apples in years (continuous)	19.269	10.799
Perceived perception characteristics			
Perceived knowledge of orchard disease	I know clearly about the pest situation in my orchard (1=yes, 0=no)	0.635	0.482
Perceived knowledge of orchard pest	I know clearly about the disease situation in my orchard (1=yes, 0=no)	0.690	0.463
Farm management practice characteristics			
Farm size (ln)	Family total farmland (continuous, mu)	1.894	0.940
Labor force	The quantity of labor force in agriculture (continuous)	2.114	1.849
Cooperative	Member of cooperatives (1=yes, 0=no)	0.361	0.481
Plot	Number of apple planting plot (continuous)	3.363	2.680
Insurance	Whether to buy agricultural insurances for orchard (1=yes, 0=no)	0.253	0.435
Access to digital information	The frequency of using the internet to enquiry the information of agricultural technologies (1=yes, 0=no)	0.552	0.498
External characteristics			
Technical training	Whether it's difficult for you to get the training of planting apple? (1=yes, 0=no)	0.479	0.500
Financial service	Whether the government's material subsidies and rewards affect respondents' agricultural activities (1=yes, 0=no)	0.264	0.441
Regulation	Whether the government's relevant environmental regulations restrict respondents' agricultural activities (1=yes, 0=no)	0.261	0.439

2.4. Survey design and data collection

Bohai Bay and the Loess Plateau are the two major apple production areas in China, which account for 86 and 90% of apple acreage and yield in China, respectively (Xie *et al.* 2014). This research was conducted in five provinces (i.e., Shandong, Shanxi, Shaanxi, Gansu, and Hebei) as a representative region for data collection. Ethical approval for this study was granted by the ethical committee of Newcastle University in 2019 (Ref: 18226/2019). Data were collected from September 2019 to January 2020 using random sampling combined with snowball sampling, with surveys completed by face-to-face interviews with farmers. Random sampling was initially used to identify one or two counties in each province and one or two towns in each selected county. In total, 560 sample farmers from the pool provided by the village leaders were selected randomly for inclusion in this study.

The survey asked questions about apple planting (e.g., farm scale, the current demands of apple production management technologies, and farmers' attitudes toward precision pesticide technologies). Following the exclusion of surveys with incomplete information, 545 surveys were used in the final analysis. In terms of sample characteristics, 88.99% of surveyed farmers were men; 47.89% were aged between 51 and 65 years; 48.07% received junior high school education and 24.59% reported primary and above; 35.41% reported being members of cooperatives; 67.34% of surveyed farmers farmed 10 mu or less of arable land (Table 2).

3. Results

3.1. Farmers' adoption decisions regarding precision pesticide technologies

Farmers' WTA precision pesticide technologies Farmers' WTA precision pesticide technologies was assessed through analysis of their adoption intentions for purchasing services or equipment. The majority of respondents (78.72%) were willing to use precision pesticide technologies through services provided by organizations such as cooperatives and professional agricultural enterprises, and 69.72% indicated that they were willing to buy the equipment for precision pesticide technologies (Fig. 2).

The heterogeneity of farmers' characteristics was assessed in terms of farmers' WTA precision pesticide technologies (Table 3). Most female farmers (83.39%) reported that they would purchase precision-technology services, and 68.35% of male farmers reported that they would buy the equipment. Farmers aged 35 years and younger (87.77%) indicated they would purchase precision pesticide technology services, and those aged between 35 and 50 (74.92%) indicated they would purchase equipment. Farmers who had received 10 to 12 years of education (e.g., high school or equivalent) (86.55%) indicated they would purchase precision agriculture services, and 73.29% of farmers whose years of schooling were 13 and more reported that they would adopt precision pesticide technologies by buying equipment. Farmers with cooperative membership reported that they would buy both services and equipment. Farmers who would buy precision pesticide technology services and equipment accounted for 94.16 and 96.44%, respectively, of those whose orchard farm size was 10–20 and 50 mu and above. Almost 80% of farmers in the Loess Plateau indicated they would buy the equipment. Farmers who managed a farm of 10–20 mu and those located in the Loess Plateau were more likely to pay for precision pesticide technology services (adoption

Table 2 Demographic characteristics of respondents

Type	Options	Number of sampling households	Percentage (%)
Gender	Male	485	88.99
	Female	60	11.01
Age (years)	≤35	31	5.69
	36–50	205	37.61
	51–65	261	47.89
	66 and above	48	8.81
Education degree	≤6	134	24.59
	7–9	262	48.07
	10–12	130	23.85
	≥13	19	3.49
Member of cooperatives	Yes	193	35.41
	No	352	64.59
Land area (mu)	≤10	367	67.34
	10–20	144	26.42
	20–50	24	4.40
	50 and above	10	1.83
Region	Bohai Bay	175	32.11
	Loess Plateau	370	67.89

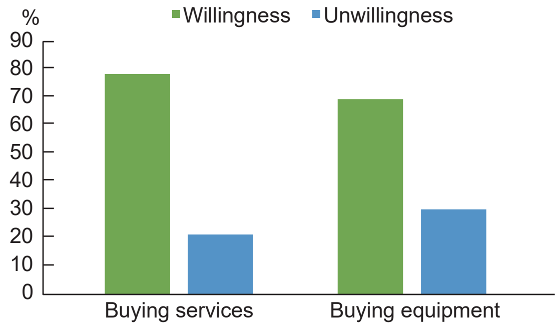

Fig. 2 Farmers' willingness to adopt (WTA) precision pesticide technologies.

Table 3 Farmers' willingness to adopt (WTA) precision pesticide technologies by characteristics

Farmers' characteristics	Percentage (%)[1)]	
	Service	Equipment
Gender		
Male	80.33	68.35
Female	83.39	48.32
Age (years)		
≤35	87.77	64.64
36–50	85.99	74.92
51–65	80.85	62.21
66 and above	70.59	59.84
Education (years)		
≤6	78.68	55.84
7–9	80.96	67.33
10–12	86.55	68.95
≥13	77.27	73.29
Member of cooperatives		
Yes	86.48	76.76
No	77.37	59.34
Land area (mu)		
≤10	75.57	58.49
10–20	94.16	76.79
20–50	81.77	85.67
50 and above	78.92	96.44
Region		
Bohai Bay	64.37	33.32
Loess Plateau	90.57	79.68

[1)] Percentage means the percentage of farmers in that group who are willing to adopt.

rates of above 90%). More farmers with farm sizes larger than 50 mu (96.44%) (3.33 ha) indicated that they would purchase precision pesticide technologies.

Farmers' WTP for precision pesticide technologies Farmers' WTP for services or equipment is summarized in Fig. 3. The values of farmers' WTP (CNY mu^{-1}) for services were primarily within the three price sections, 100 and 150 CNY, 50 and 75 CNY, and 25 to 50 CNY, accounting for 22.35, 18.64, and 13.23%, respectively. In terms of WTP (CNY yr^{-1}) for precision pesticide technologies, preferred price levels were 1 000 to 2 000 CNY, 2 000 to 3 000 CNY, and less than 1 000 CNY, with a rate of 30.53, 22.12, and 14.17%, respectively.

Farmers' WTP is analyzed against demographic characteristics (Fig. 4). Men were more willing to pay more than women, with a WTP of 136.99 CNY for buying the services of precision pesticide technologies, while women were willing to pay more to install the equipment. Farmers who were 35 years old and younger reported the highest WTP for purchasing precision pesticide technology services and equipment (165.34 CNY mu^{-1} and 5 265.19 CNY yr^{-1}). Farmers who had received more than 12 years of education reported their WTP for the services and equipment were 134.27 CNY mu^{-1} and 6 136.48 CNY yr^{-1}, respectively. Farmers who participated in cooperatives reported higher WTP in relation to both buying the services and the equipment. Farmers located on the Loess Plateau reported a higher WTP than those in Bohai Bay (146.27 CNY mu^{-1} for buying the services and 6 258.36 CNY yr^{-1} for buying the equipment). The WTPs for equipment of farmers whose farm size was 50 mu and above and 20–50 mu were 31 115.33 and 6 523.15 CNY yr^{-1}, respectively. Therefore, cooperative membership and larger farm scale were positively associated with farmers' WTP for precision pesticide technologies.

3.2. Determinants of farmers' adoption decision about precision pesticide technologies

Determinants of farmers' WTA precision pesticide technologies Farmers' WTA was the first hurdle when extending advanced agricultural technologies. Table 4 shows the factors that impacted farmers' WTA the services and equipment of precision pesticide technologies and their marginal effects separately.

When making adoption decisions about the services of precision pesticide technologies, farmers' WTA was affected by their perceptions, farm management practices, and external characteristics. The results showed that farmers' perceived knowledge of diseases had a positive impact on farmers' WTA precision pesticide technologies, while perceived knowledge of pests in the orchard had a negative impact. For farm management, cooperative membership and access to digital information all positively impacted farmers' WTA precision pesticide technologies, while land plots had a negative impact. Regarding external characteristics, financial services positively affected farmers' WTA precision pesticide technologies. For personal characteristics, gender and age positively affected farmers' WTA, and the square terms of age negatively impacted farmers' WTA precision pesticide technologies through purchasing services.

Farmers' adoption decisions about purchasing

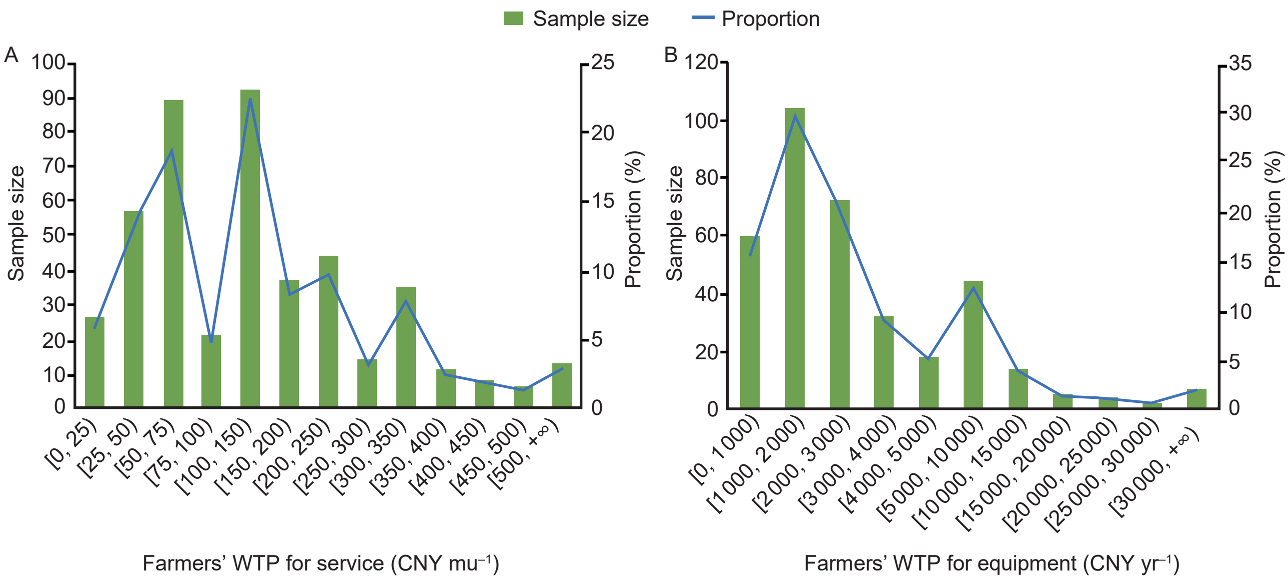

Fig. 3 Farmers' willingness to pay (WTP) for precision pesticide technologies.

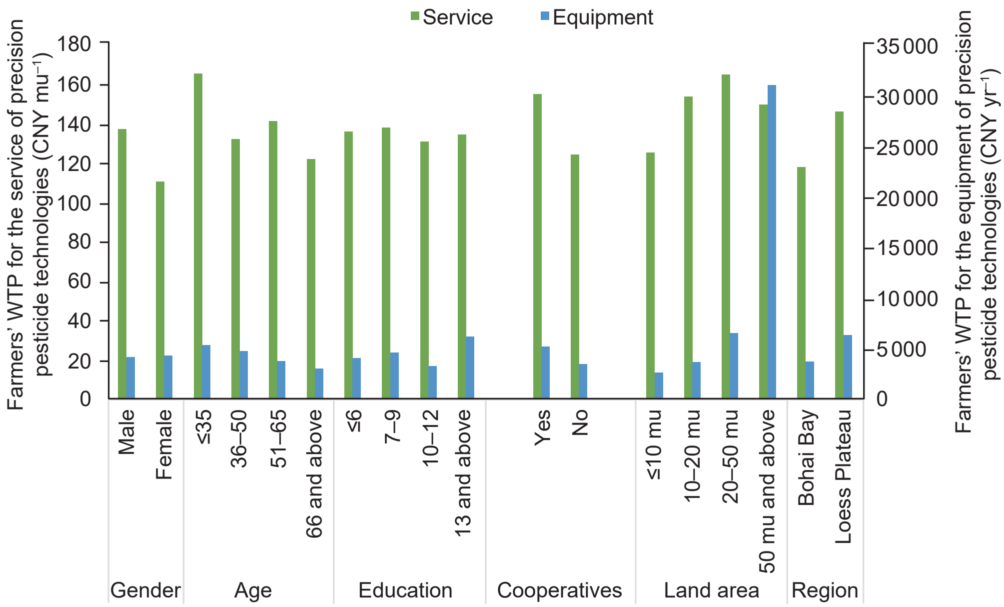

Fig. 4 Farmers' willingness to pay (WTP) for precision pesticide technologies in different groups.

Table 4 Empirical results of farmers' willingness to adopt (WTA) precision pesticide technologies

Variable	Service		Equipment	
	Marginal effect	St. Err.	Marginal effect	St. Err.
Perceived perception				
Perceived knowledge of disease	0.114*	0.064	0.201***	0.078
Perceived knowledge of pest	–0.157**	0.079	–0.172*	0.095
Farm management practice				
Farm size (Ln)	0.056	0.056	0.074**	0.033
Labor force	–0.004	0.020	0.017	0.023
Cooperative	0.079**	0.043	0.067**	0.029
Plot	–0.007*	0.005	–0.015	0.012
Insurance	0.025	0.114	0.145***	0.056
Access to digital information	0.092**	0.048	0.103***	0.042
External characteristics				
Technical training	0.023	0.020	–0.008	0.018
Financial service	0.095***	0.028	0.103	0.066
Environmental regulation	–0.027	0.021	0.082**	0.042
Personal characteristics				
Gender	–0.096**	0.048	0.091	0.059
Age	0.024*	0.011	0.008	0.010
Age^2	–0.000**	0.000	–0.000	0.000
Education	0.010	0.007	–0.015	0.015
Education^2	–0.001**	0.000	0.001	0.001
Farming experience	0.002	0.005	0.008***	0.003
Farming experience^2	–0.000	0.000	–0.000	0.000
Region	Controlled		Controlled	

*, **, and *** denote significance at 10, 5, and 1% levels, respectively; St. Err. refers to clustered robust standard errors.

precision pesticide technology equipment were mainly influenced by personal characteristics, perceptions, their farm management practices, and external characteristics. Farmers' perceived knowledge about orchard diseases had positive impacts on adoption decisions, and perceived knowledge regarding pests in the orchard had negative impacts, which was consistent with the estimated results for farmers' adoption decisions regarding purchasing services. Farm management practice characteristics, farm size, cooperative membership, insurance, and access to digital information showed a positive impact on precision agriculture adoption through equipment purchase. Environmental regulation significantly positively impacted farmers' WTA the equipment of precision agriculture. Farmers' experience had positive impacts on farmers' WTA precision pesticide technologies through purchasing equipment.

Determinants of farmers' WTP for precision pesticide technologies If apple farmers decided to adopt precision pesticide technologies, a second hurdle estimation was made. The factors that impacted farmers' WTP for the services and equipment of precision pesticide technologies and their marginal effects are shown in Table 5.

WTP for precision technology services was mainly impacted by farm management practices, external characteristics, and personal characteristics. Specifically, farmers' farming experience negatively impacted farmers' WTP, whereas membership in a cooperative, access to digital information, technical

Table 5 Empirical results of farmers' willingness to pay (WTP) for precision pesticide technologies

Variable	Service		Equipment	
	Marginal effect	St. Err.	Marginal effect	St. Err.
Perceived perception				
Perceived knowledge of disease	0.090	0.152	0.053	0.142
Perceived knowledge of pest	0.105	0.150	0.097	0.158
Farm management practice				
Farm size (ln)	–0.011	0.073	0.169**	0.084
Labor force	0.021	0.038	0.051	0.064
Cooperative	0.281*	0.160	0.226***	0.071
Plot	0.020	0.014	–0.008	0.007
Insurance	–0.171	0.326	–0.006	0.133
Access to digital information	0.151*	0.089	0.273*	0.150
External characteristics				
Technical training	0.196*	0.102	0.191***	0.058
Financial service	–0.074	0.096	–0.094	0.174
Environmental regulation	0.244***	0.059	0.322*	0.171
Personal characteristics				
Gender	0.166*	0.097	–0.197	0.212
Age	–0.004	0.070	–0.071	0.077
Age^2	0.000	0.001	0.001	0.001
Education	–0.011	0.054	0.022	0.049
$Education^2$	0.000	0.003	–0.001	0.003
Farming experience	–0.023***	0.007	–0.012	0.011
Farming $experience^2$	0.000***	0.000	0.000	0.000
Region	Controlled		Controlled	
Constant	4.175***	1.596	8.476***	1.713

*, **, and *** denote significance at 10, 5, and 1% levels, respectively; St. Err. refers to clustered robust standard errors.

training, and environmental regulation showed positive impacts. Gender and farming experience had significant impacts on farmers' WTP, and the square terms of farming experience significantly impacted farmers' WTP for precision agriculture services.

Farmers' WTP for precision technology equipment was mainly influenced by personal characteristics, external characteristics, and farm management practices. A larger farm size, cooperative membership, and access to digital information positively impacted farmers' WTP for precision technology equipment. Technical training and environmental regulation were also positively correlated with the WTP for equipment.

4. Discussion

4.1. Farmers' precision pesticide technology adoption

The overuse of chemical pesticides in agriculture requires interventions to improve pesticide use efficiency within the agricultural sectors, including at the farm scale. One possible mitigatory activity is the application of precision pesticide technologies. Our results indicated that 78.72% of orchard farmers in the research area were willing to adopt precision pesticide technologies through buying services, compared with 69.72% who were eager to purchase the equipment. This partially confirms Zhang and Zhang (2016), who reported that rice farmers in China are highly willing to purchase innovative production services from professional agricultural enterprises. There are two possible reasons. First, as agricultural service system provision is maturing, it is more convenient and economical for farmers to access pesticide precision technologies through service providers, particularly for smallholder farmers with fragmented farmland concerned with the high cost of purchasing equipment (Mi *et al.* 2020). Second, purchasing precision pesticide equipment requires acquiring new skills on the part of the farmer, which may discourage farmers' adoption willingness (Wilson 2021).

The heterogeneity analysis of farmers' characteristics found that farmers' WTA and WTP for precision pesticide technologies varied according to farmers' characteristics. Farmers who were younger, working at a moderate-scaled farm, and the members of cooperatives were more willing to purchase services. Farmers' WTA buying precision pesticide technology equipment increased with farm scale. Farmers who were younger or participated in cooperatives had higher WTA. In terms of WTP, both cooperative membership and larger farm scale had positive influences on improving farmers' WTP for both services and equipment.

This implies that stakeholders should target extension projects which take account of farmers' characteristics as priorities and preferences. For example, manufacturers of precision agricultural technologies might assess the technical needs of farmers who operate different land scales and design technologies accordingly. Policymakers might ensure cooperatives have access to and disseminate relevant information about new technologies.

4.2. Determinants of precision pesticide technology adoption in an orchard system

Farmers' knowledge about the prevalence of pests and diseases in their orchards increased their WTA precision pesticide technologies. For example, the more farmers knew about disease prevalence in orchards, the more likely they were willing to adopt precision pesticide technologies (Chen *et al.* 2018). However, farmers' perception of knowledge of pest prevalence negatively affected their WTA precision pesticide technologies. Therefore, dissemination activities such as agricultural subscriptions through social media and agricultural training linked to extension services may improve farmers' knowledge about disease management, increasing farmers' precision pesticide technology adoption.

Farm size had significant and positive effects on farmers' WTA the equipment of precision pesticide technologies. Specifically, the larger the operating land area associated with a particular farm, the higher WTA and WTP for the equipment. The estimated marginal effect indicated that land scale increased the likelihood of WTA and WTP associated with equipment by 7.4 and 16.9%, respectively (Shang *et al.* 2021). However, installing equipment may require a minimum farm size scale. In addition, a larger farm scale may help farmers decrease the marginal costs associated with agricultural inputs. Therefore, large-scale farming may incentivize farmers to adopt and operationalize higher WTP for precision pesticide technologies. It is notable that farm scale had significant marginal effects on farmers' WTA and WTP for equipment and did not significantly impact precision pesticide services. With more young farmers immigrating from the countryside to the city to work, the older farmers are not able to produce without support. Compared with purchasing services from professional agricultural enterprises or cooperatives, farmers who farm at a larger farming scale may be more able to recover the costs of purchasing precision technology equipment. While this suggests that precision farming technologies might be more effectively developed to meet the needs of larger farms, it is also relevant to develop technological innovations, extension services, and service provisions aiming at smaller-scale farms in the future for realizing environmental targets.

The results also indicated that farmers who participated in cooperatives were more likely to report a higher WTA, as well as indicating a higher WTP for precision pesticide technologies. The estimated marginal effect showed that cooperative membership increased WTA services and equipment by 7.9 and 6.7%, respectively; it also increased WTP for services and equipment by 28.1 and 22.6%, respectively. Cooperatives may represent a source of information in addition to extension services and the technology providers for farmers about new technologies (Li *et al.* 2021). In most cases, cooperatives are associated with collective action and social capital. Farmers perceive them to be a useful channel to obtain information about innovative technologies, which can consequently increase farmers' WTA (Abebaw and Haile 2013; Kolade and Harpham 2014). Dissemination strategies can be linked to cooperative activities to provide relevant information to facilitate farmers' WTA and WTP for new agricultural technologies which benefit the environment.

The role of access to digital information appears to play a significant role in promoting precision pesticide technology adoption through services and equipment acquisition. The estimated marginal effect showed that applying access to digital information increased the WTA services and equipment by 9.2 and 10.3%, respectively, while WTP for services and equipment were increased by 15.1 and 27.3%. These results suggested that farmers with high access to digital information are more likely to adopt precision pesticide technologies. Agricultural informatization can bring timely and accessible agricultural information to farmers in a targeted approach (Zhang *et al.* 2016). Farmers using the Internet to acquire agricultural technology information may be more likely to get timely information on innovative technologies and, therefore, more willing to adopt with a higher WTP (Gao *et al.* 2020). Training can be implemented to improve farmers' ability to access agricultural information online. The adoption of novel precision technologies might be further accelerated through developing application interfaces on portable devices, which may further catalyze adoption.

Technical training increased farmers' WTP for precision technologies. The estimated marginal effect showed that having technical training increased farmers' WTP for services and equipment by 19.6 and 19.1%, respectively. Through technical training, farmers can be presented with robust, science-based evidence and relevant information about new technologies, including economic viability, impacts on sustainable production, risks, and other potential implications for their farm operations and budgets (Liu *et al.* 2019). Thus, technical training could be an effective incentive to adoption, resulting in farmers' higher WTP for precision technologies.

Financial services positively affected farmers' WTA precision technologies. The estimated marginal effect showed that having access to a convenient financial services increased the probability of WTA services by 9.5%. Farmers regard access to financial support as one of the essential determinants of the economic viability of agricultural technology innovation (Vorobeva *et al.* 2022). In comparison with conventional agricultural technologies, the adoption of precision pesticide technologies may require additional financial investments by farmers, which may represent an economic burden for farmers. This burden could be alleviated by the provision of a loan from a financial service provider. Heterogeneity in farmers' decision-making was identified at the two stages of the "hurdle" analysis. Specifically, farmers' WTA and WTP for the equipment of precision pesticide technologies were both affected by farm size, farmers' participation in a cooperative, and access to digital information. Targeted information strategy and technology development should be differentiated to meet farmer and farm requirements.

Personal characteristics, including gender, age, farming experience, and their square terms of the variables, had positive impacts on farmers' decisions on precision technologies. The marginal results showed that female farmers were more likely to increase the probability of WTA services by 9.6%. In contrast, male farmers increased the probability of WTP for services by 16.6%. In rural China, male workers are usually the household head and the decision-maker in relation to economic expenditure. Therefore, male farmers are more likely to give a higher price for WTP for precision pesticide technologies. The effects showed that age, agricultural experience, and their square terms had significant impacts on farmers' WTA and WTP for precision technology services. The age and agricultural experience coefficients implied an inverted U-shaped relationship between age and farmers' WTA precision pesticide technologies, with the turning value of age at 49.47. A U-shaped relationship existed between agricultural experience and farmers' WTP for precision pesticide technology services, and the turning value of the agricultural experience was 11.5 years. The results showed potential nonlinear relationships between these variables and farmers' WTA and WTP for precision pesticide technology. Therefore, specific farmers should be targeted according to their personal characteristics, including age and agricultural experience, to provide relevant information to facilitate their WTA and WTP for new agricultural technologies.

5. Conclusion

Precision pesticide technologies have the potential to facilitate the effective use of pesticides, with concomitant health and environmental benefits. However, limited attention has focused on analyzing farmers' WTA and WTP for precision pesticide technology services and equipment. This research applied a double hurdle approach to investigate what factors facilitated and constrained Chinese orchard farmers' to adopt precision pesticide technologies. The results indicated that 78.72% of apple growers in the Loess Plateau and Bohai Bay were WTP for the services provided by service organizations, and 69.72% were WTP for equipment themselves for adopting precision pesticide technologies. At present, farmers have higher WTA precision pesticide technologies through purchasing services than through purchasing equipment. Therefore, understanding how to access such services may be an effective route to promote technology adoption through dissemination, education, and extension activities.

Farmers' two-stage decision-making was mainly affected by their perceptions (e.g., perceptions of orchard diseases and pests), farm management practices, and external characteristics. Dissemination activities, such as agricultural subscriptions through social media, agricultural training, and other continuing professional development activities, may increase farmers' evaluations of the benefits of adopting precision pesticide technologies. Various extension policies can be made according to farmers' farm scale. For example, the government can focus on small- and moderate-scale farmers to promote the services of precision pesticide technologies, and subsidy policies can be tilted to large-scale farmers to encourage installation of precision pesticide technology equipment. Agricultural informatization is a critical factor affecting farmers' WTA and can be used to disseminate the benefits of adopting precision pesticide technologies. The results emphasize the importance of developing and implementing policies that create a favorable environment or provide policy levers. These can further promote precision pesticide technologies among farmers and deliver against environmental goals. Moreover, there were nonlinear relationships between age, agricultural experience, and farmers' decisions about precision pesticide technology services. Therefore, the specific farmers should be targeted, according to personal characteristics, including age and agricultural experience, to provide relevant information to facilitate farmers' decision-making for advanced agricultural technologies.

While this research contributes to the literature on factors that significantly influence farmers' WTA and WTP for precision pesticide technologies, a few limitations should be noted. First, this study employed non-experimental, cross-sectional data to analyze farmers' precision pesticide technology adoption. However, the causal effect between the significant factors and farmers' WTA and WTP for precision pesticide technologies is worth analyzing. Longitudinal data with experimental research designs could be considered in future studies to address the causality between significant determinants for farmers' WTA and WTP. Besides, farmers who migrated from rural to urban areas as non-farming workers were not sampled in this study due to time and funding limitations. Therefore, future research should also give insights into the determinants of precision pesticide technologies among this farmer subgroup.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

Appendix associated with this paper is available on http://www.ChinaAgriSci.com/V2/En/appendix.htm

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